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N94-25359

LOADING, ELECTROMYOGRAPH, AND MOTION DURING EXERCISE

Final Report
NASA/ASEE Summer Faculty Fellowship Program-1993
Johnson Space Center

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Date Submitted:	July 12, 1993
Contract Number:	NGT-44-001-800

ABSTRACT

A system is being developed to gather kineto-dynamic data for a study to determine the load vectors applied to bone during exercise on equipment similar to that used in space. This information will quantify bone loading for exercise countermeasures development. Decreased muscle loading and external loading of bone during weightlessness results in cancellous bone loss of 1% per month in the lower extremities and 2% per month in the calcaneus. It is hypothesized that loading bone appropriately during exercise may prevent the bone loss. The system consists of an ergometer instrumented to provide position of the pedal (foot), pedaling forces on the foot (on the sagittal plane), and force on the seat. Accelerometers attached to the limbs will provide acceleration. These data will be used as input to an analytical model of the limb to determine forces on the bones and on groups of muscles. EMG signals from activity in the muscles will also be used in conjunction with the equations of mechanics of motion to be able to discern forces exerted by specific muscles. The tasks to be carried out include: design of various mechanical components to mount transducers, specification of mechanical components, specification of position transducers, development of a scheme to control the data acquisition instruments (TEAC recorder and optical encoder board), development of a dynamic model of the limbs in motion, and development of an overall scheme for data collection analysis and presentation. At the present time, all the hardware components of the system are operational, except for a computer board to gather position data from the pedals and crank. This board, however, may be put to use by anyone with background in computer based instrumentation. The software components are not all done. Software to transfer data recorded from the EMG measurements is operational, software to drive the optical encoders' card is mostly done. The equations to model the kinematics and dynamics of motion of the limbs have been developed, but they have not yet been implemented in software. Aside from the development of the hardware and software components of the system, the methodology to use accelerometers and encoders and the formulation of the appropriate equations are an important contribution to the area of biomechanics, particularly in space applications.

INTRODUCTION

The principal objective of the project in which the Faculty Fellow was involved was to be able to measure forces on the bones, and forces exerted by individual muscles, during ergometer exercise. This information is necessary to study the mechanism and to suggest solutions to the problem of bone loss experienced by astronauts in zero gravity conditions. In cancellous bone the rate of bone loss is significant even in short durations trips to space (1% per month in the lower extremities and 2% per month in the calcaneus).

The exercise machine to be used is an ergometer, since they are available in the space shuttles for use by the astronauts to maintain their physical integrity. Biomechanic studies of bicycling done by various researchers have been used as reference to define the variables to be measured and their ranges.

This report describes the system developed to measure the forces on bones and the forces exerted by groups of muscles in the lower extremities. The system consists of an ergometer instrumented with load cells in the pedals, angular position encoders in the crank and pedals, and accelerometers attached to the body sections.

SUMMARY OF THE METHODS

To determine forces, the acceleration of the center of mass of each member must be determined, as well as the location of the center of mass, the total mass, and the moment of inertia. The accelerations must be known for every position of the member as it traverses the path dictated by the exercise. The general approach will be to measure the acceleration vector of various points on the member (two points for planar motion) and calculate the acceleration of the center of gravity from these measurements. Newton's Law of motion will then provide equations relating forces and moments applied to the member. Some forces will be measured using load cells, which will allow the determination of forces exerted by groups of muscles and forces at the joints. Forces exerted by particular muscles will be latter separated using EMG signals and possibly other methods such as certain assumptions about the sharing of forces by different muscles, correlations, and minimization/maximization of cost functions.

To determine acceleration of the center of mass, the acceleration vector of two points (for motion on the sagittal plane) will be measured using miniature accelerometers. The acceleration vector will be expressed with respect to a coordinate system attached to the member. The orientation of this coordinate system will be determined using the acceleration of a known point in both coordinate systems (a base coordinate system, and the one attached to the member). The relative rotation of the two coordinate systems will be determined by the equations that relate the orthogonal components of the same acceleration vector expressed in the two coordinated systems rotated with respect to each other.

Using accelerometers on Earth requires that the component of the acceleration of gravity along the direction of the accelerometer axis be factored out¹. This will be done by considering the hip joint fixed, thus forming a five bar linkage² (bicycle crank, foot, calf, thigh, and bicycle body).

Since the position of the leg/foot joint is measured using encoders on the crank and pedal, the position of the knee joint can be calculated. This method provides the orientation of the axes attached to each member with sufficient accuracy to perform gravity compensation on the accelerometers.

Forces on each member will be determined using Newton's Second Law. Forces on the foot will be measured using a pedal instrumented with load cells. Three equations of motion of the foot will allow determination of three unknowns that may be a force with known direction at the joint, and forces or moments by two other groups of muscles. A similar approach will be used to determine forces at the other

joints and forces applied by groups of muscles. Assumptions regarding sharing of force by the various muscles in one group will be used to further identify the force on specific muscles. Further, minimization/maximization of cost functions and EMG signals will be used to identify forces on particular muscles ^{2,3,4}.

Body segment dimensions and mass properties will be determined from X-ray and densitometer image analysis.

DESCRIPTION OF THE HARDWARE

The hardware includes and ergometer, a 28 channel recorder⁵, three rotary optical encoders⁶, accelerometers⁷, load cells⁸, 486 class personal computer fitted with three cards, (1) a GPIB interface card to control the recorder⁹, (2) a four channel decoder card to read the encoder information¹⁰, and (3) a 32 channel A/D board to digitize data from the recorder. During an exercise

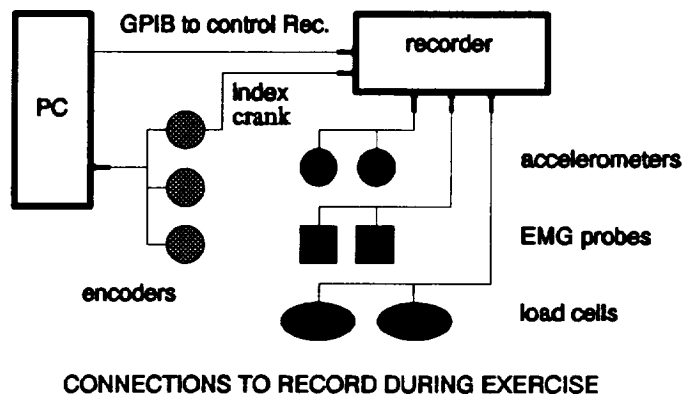


Figure 1 Hardware connections during the experiment

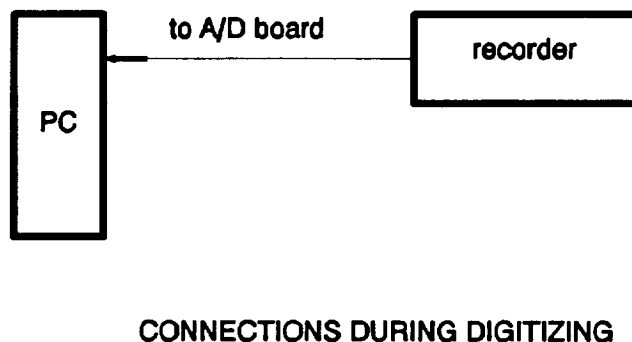


Figure 2 Hardware connections to digitize recorder data prior to their use in the kineto-dynamic formulations.

experiment, data from the accelerometers and EMG probes is recorded in the recorder while position information is digitized using the encoder card. To synchronize the two sets of data, an index pulse generated by the crank encoder in every revolution is also recorded. When the experiment is done, the data is digitized using the A/D board and is synchronized with the data from the encoders before it can be used in the motion equations.

The ergometer was modified slightly so that an encoder could be installed at the crank, and one encoder in each pedal axis. The pedals are fitted with fixtures to hold the load cells that measure force in the sagittal plane. The pedal fixtures were designed by JSC Colleague, Dr. Taggart.

KINEMATIC ANALYSIS

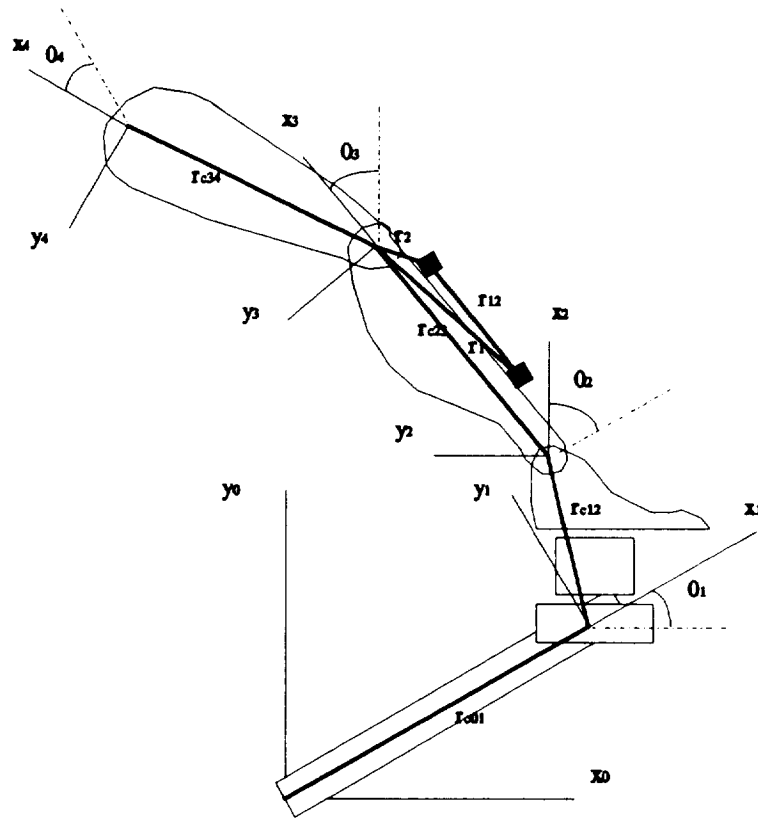
This section describes the methods to determine the acceleration of the center of gravity and the angular velocity and angular acceleration of a section. These variables are needed in the dynamic equations to determine the forces on the section.

Figure 3 shows a schematic of the elements encompassing the system. Five coordinate frames are defined, one inertial frame attached to the ergometer structure at the crank joint ($x_0y_0z_0$), and the others attached to the crank ($x_1y_1z_1$), the pedal and foot ($x_2y_2z_2$), the calf ($x_3y_3z_3$), and the thigh ($x_4y_4z_4$). The frames were defined borrowing a methodology from the area of robotics, according to the Denavit-Hartenberg rules¹¹. This notation will help simplify the formulation of the equations and their implementation in MatLab programming environment.

The kinematic equations needed are those that describe plane motion with rotating and translating frames of reference. In Figure 3, the acceleration of a point such as the center of gravity of the calf, knowing the acceleration of the origin of frame $x_3y_3z_3$ is defined by the following equation.

$$a_{g3} = a_{o3} + \alpha_3 \times r_{g3} + \omega_3 \times (\omega_3 \times r_{g3}) \quad (1)$$

where ω_3 is the angular velocity of the section, α_3 is the angular acceleration, and a_{o3} is the acceleration of the origin of the coordinate system attached to the calf. Equation (1) may be used to determine the accelerations of the origin of Frame 1, knowing that the acceleration of frame 0 is zero, and that the angular velocity and acceleration of the crank are provided by the crank encoder. Subsequently, the acceleration of the foot/pedal-attachment section (Frame 2) may be calculated using the previously calculated acceleration of the origin of Frame 1, and the angular acceleration and angular velocity of Frame 2 with respect to Frame 1 (pedal encoder). The angular acceleration of Frame 2 is given by the sum of the angular accelerations inferred from the crank and pedal encoders, and the angular velocity of Frame 2 is given by the sum of the angular velocities inferred from the crank and pedal encoders. The specific equations are as follows:



$$\ddot{r}_{c01} = \omega_1 \times (\omega_1 \times r_{c01}) + \alpha_1 \times r_{c01} \quad (2)$$

where ω_1 is the angular velocity, and α_1 is the angular acceleration measured by the crank encoder.

$$\ddot{r}_{c02} = \ddot{r}_{c01} + \omega_2 \times (\omega_2 \times r_{c12}) + \alpha_2 \times r_{c12} \quad (3)$$

where ω_2 is the sum of the angular velocities of the crank and pedal encoders, and α_2 is the sum of the angular accelerations measured by the crank and pedal encoders.

At this point, the acceleration of the foot joint has been determined. Next, the angular acceleration and velocity of the calf (Frame 3) will be determined using measurements from the accelerometers. Note that all the accelerometers measure acceleration expressed in Frame 3, but the accelerations are absolute. Therefore, the following formulas will have all the vectors involved expressed in Frame 3 directions. Figure 4 shows the placement of the accelerometers on the calf. Each accelerometer measures acceleration in the x_3 and y_3 directions.

$$\ddot{\mathbf{x}}_2 = \ddot{\mathbf{x}}_1 + \boldsymbol{\omega}_3 \times (\boldsymbol{\omega}_3 \times \mathbf{r}_{12}) + \boldsymbol{\alpha}_3 \times \mathbf{r}_{12} \quad (4)$$

where the angular acceleration and velocity vectors are the unknowns. Using the components of the accelerations measured by the accelerometers, the accelerations at the point of placement of the accelerometers can be expressed as follows.

$$\begin{aligned} \ddot{\mathbf{x}}_1 &= (a_{x1}, a_{y1}) \\ \ddot{\mathbf{x}}_2 &= (a_{y2}, a_{y2}) \\ \mathbf{r}_{12} &= (r_x, r_y, r_z) \end{aligned} \quad (5)$$

Expanding the cross products in Equation (4),

$$a_{x2} = a_{x1} + \alpha_y r_z - \alpha_z r_y + \omega_x \omega_y r_y + \omega_z \omega_x r_z - r_x (\omega_y^2 + \omega_z^2) \quad (6)$$

$$a_{y2} = a_{y1} + \alpha_z r_x - \alpha_x r_z + \omega_x \omega_y r_z + \omega_z \omega_y r_x - r_y (\omega_x^2 + \omega_z^2) \quad (7)$$

$$a_{z2} = a_{z1} + \alpha_x r_y - \alpha_y r_x + \omega_x \omega_z r_x + \omega_y \omega_z r_y - r_z (\omega_x^2 + \omega_y^2) \quad (8)$$

For the case of plane motion, the following assumptions are valid: $r_z \approx 0$ (acceleration is about an axis perpendicular to the vector joining the accelerometers throughout the entire motion), $\omega_x \approx 0$, and $\omega_y \approx 0$ (no twist or yaw). Applying these assumptions the above equations can be simplified further.

$$\begin{aligned} r_y \alpha_z + r_x \omega_z^2 &= a_{x1} - a_{x2} \\ r_x \alpha_z - r_y \omega_z^2 &= a_{y2} - a_{y1} \end{aligned} \quad (9)$$

System of equations (9) may be solved for the angular accelerations and velocities of the calf section.

Since the acceleration of the foot joint is known, the acceleration of the origin of Frame 3 can be calculated using an expression similar to equation (3), where the angular acceleration and velocity are those determined from equation (9). Also, the same procedure followed to determine the angular acceleration and velocity of Frame 3 may be used to determine these variables for Frame 4. For this, two accelerometers are fixed to the thigh section which can measure acceleration along the directions of the coordinate Frame 4. Once the angular variables are obtained, using the known acceleration of the origin of Frame 3, one may calculate the

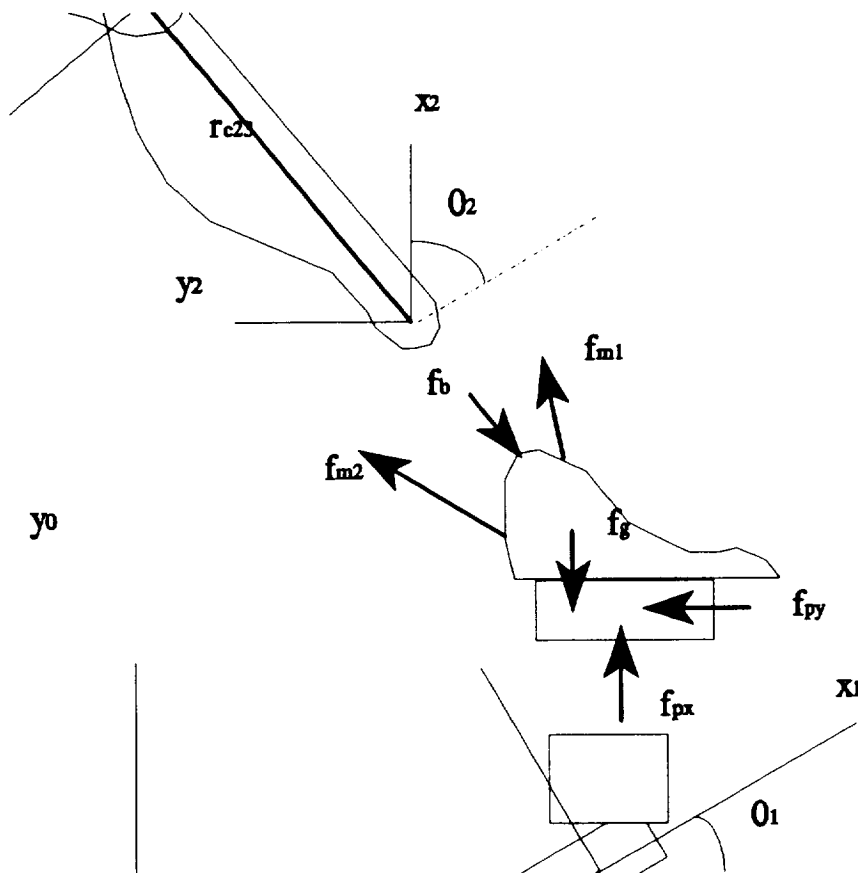


Figure 5 Free body diagram for the determination of forces on the foot/pedal section.

acceleration of the origin of Frame 4.

Finally, knowing the accelerations of all the frame origins, the acceleration of the center of gravity may be calculated using an expression similar to equation (1).

Acceleration Compensation

Accelerometers measure 1-g when oriented in the vertical direction, even when the body where they are fixed is not moving. Therefore, it is necessary to eliminate this bias prior to using the accelerometer data in the kinematic equations. All that is needed is the orientation of each frame at the moment the acceleration is measured. This information may be obtained if one can assume that the hip joint does not move. If this is the case, the frame of the exercise machine, the crank, the foot/pedal, the calf, and the thigh, define a five-bar linkage mechanism.

Knowing the position of the calf-foot/pedal joint (origin of Frame 2), and the distances from the foot/calf joint to the knee joint (r_{23}), and from the knee joint to the hip joint (r_{34}), one can write two equations to determine the angular position of Frames 3 and 4. Let r_{02} be the vector from

the origin of Frame 0 to the origin of Frame 2, r_{23} the vector from the origin of Frame 2 to the origin of Frame 3, r_{34} the vector from the origin of Frame 3 to the origin of Frame 4, and r_{04} the vector from the origin of Frame 0 to the origin of Frame 4. The following expression relates these vectors.

$$r_{23} + r_{34} = r_{04} - r_{02} \quad (10)$$

Vector equation (10) implies two scalar equations. The vectors on the left hand side may be expressed as $r_{23} = r_{23}(\cos\theta_3, \sin\theta_3)$ and $r_{34} = r_{34}(\cos\theta_4, \sin\theta_4)$. Therefore, equation (10) may be solved for the two unknown direction vectors that provide the desired orientations.

DYNAMIC ANALYSIS

Once the accelerations of the center of gravity of each section has been determined, one can apply the equation of motion to each section to determine the forces and torques being borne. Figure 5 shows the free-body diagram corresponding to the foot/pedal section. The equation of motion for this section is given by

$$\begin{aligned} f_p + f_m + f_b + f_g &= ma_g \\ f_p d_p + f_m d_m + f_b d_b &= I \alpha_3 \end{aligned} \quad (11)$$

where d_p , d_m , and d_b are the radii of gyration of the corresponding forces.

CONCLUSIONS AND RECOMMENDATIONS

A system to measure forces on bone and forces exerted by muscles during exercise using an ergometer bicycle has been designed and is almost fully implemented. Non-invasive instrumentation and methods have been developed, although further work is necessary to implement software to carry out some of the data collection, and all of the data analysis. The hardware components are compact and do not require much space, in fact, they may be easily adapted for use with the ergometer currently operating in the Space Shuttle. The methods for determination of the forces use data measured by an encoder at the crank, an encoder at the pedal, load cells at the pedal, and accelerometers fixed to the moving section of interest.

Currently the equations apply only to two dimensional motion, but may be easily extended to three dimensions by increasing the number of accelerometers used. Also, complementary methods to determine the force exerted by individual muscles need to be investigated. Some of these methods are mentioned in the introduction.

Further work is needed to describe with adequate precision the motion and forces on the muscles and bones in all the sections of the body during exercise. By making measurements on the same exercise on Earth and on Space, one may determine which exercises are suitable to maintain the astronauts health integrity, as well as synthesize new forms of exercise.

REFERENCES

1. Lawther, A. and Griffin, M. J., "Measurement of ship motion," Human Factors Research Unit, Institute of Sound and Vibration Research, Southampton University, Southampton S09 5NH, England.
2. Redfield, R. and Hull, M. L., "Prediction of pedal forces in bicycling using optimization methods," Biomechanics, Vol. 19, No. 7, pp. 523-540, 1986.
3. Harrison R. N., Lees A., and McCullagh P. J. J., "A bioengineering analysis of human muscle and joint forces in the lower limbs during running," Journal of Sports Sciences, Vol. 4, pp. 201-218, 1986.
4. Seireg, A. and Arvikar, R.J., "A mathematical model for evaluation of forces in lower extremities of the musculo-skeletal system," Biomechanics, Vol. 6, 1973, pp. 313-326.
5. 28 channel recorder, TEAC model XR-9000, TEAC America, Inc., Montebello, CA, USA.
6. Rotary optical incremental encoders models:..
7. Accelerometers Model EGAXT-10, Entran Devices, Inc., Fairfield, NJ, USA.
8. Load cells Model ELF-TC1000-250, Entran Devices, Inc., Fairfield, NJ, USA.
9. General purpose interface board Model AT-GPIB, National Instruments Corporation, Austin, TX, USA.
10. Decoder board Model 5312-4, Technology80, Inc., Minneapolis, MN, USA.
11. Spong, M. W. and Vidyasagar, M., *Robot Dynamics and Control*, John Wiley & Sons, Inc., New York, 1989, pp. 65-91.

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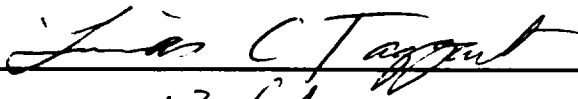
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